Improved interpretation of T_2 distributions from NMR relaxation measurements for a better prediction of low permeabilities

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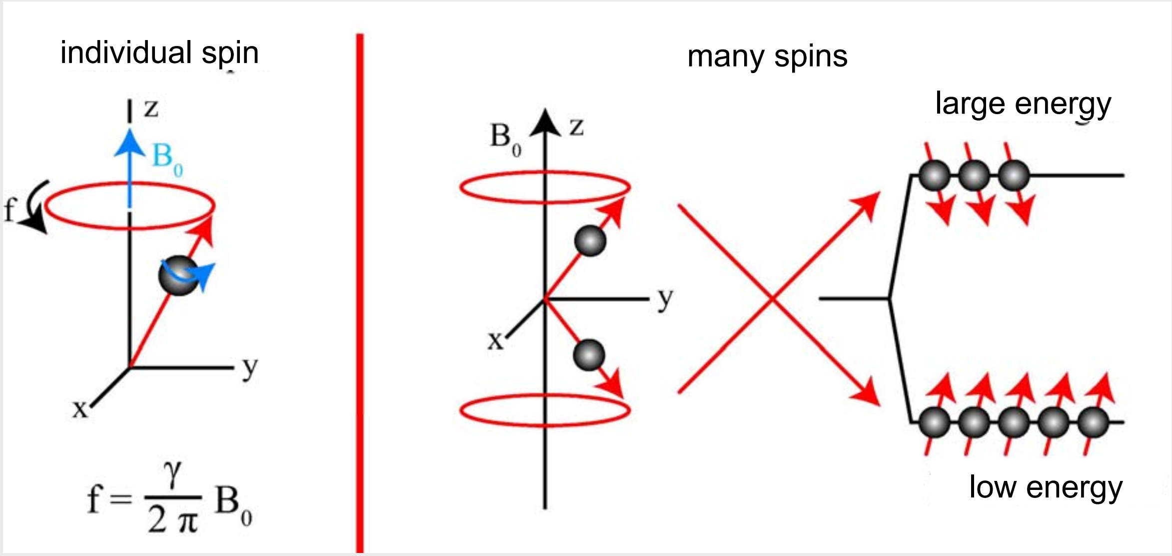
Outline

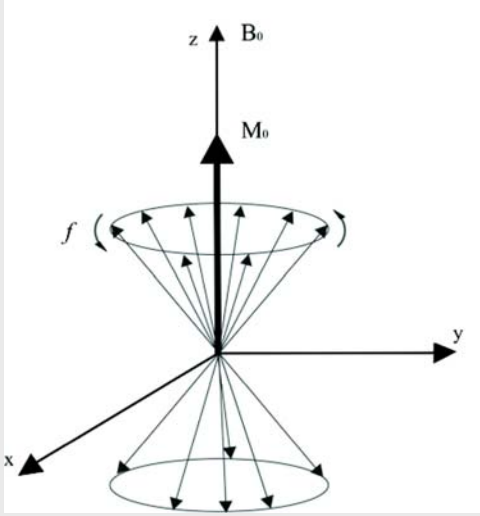
- Motivation
- NMR relaxation mechanisms
- NMR Instrumentation
- New model theory
- Permeability results
- Conclusions

Motivation

- Permeability prediction from measured NMR decay times (T_2)
- Mobile NMR core-scanner for rapid well-site analysis

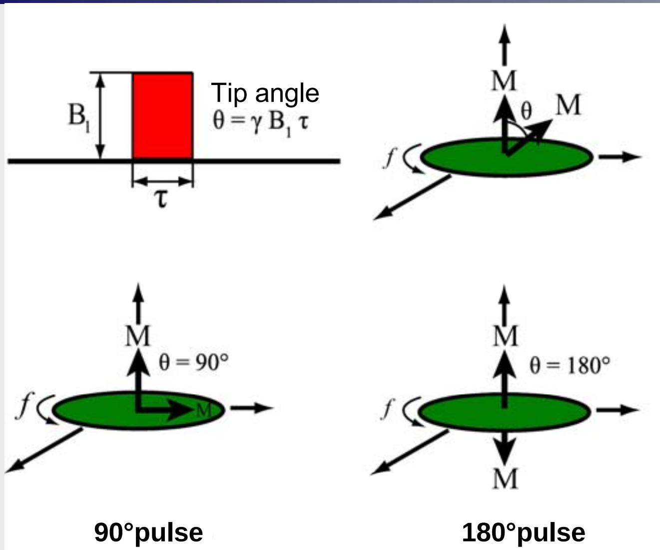
NMR Relaxation - T_1

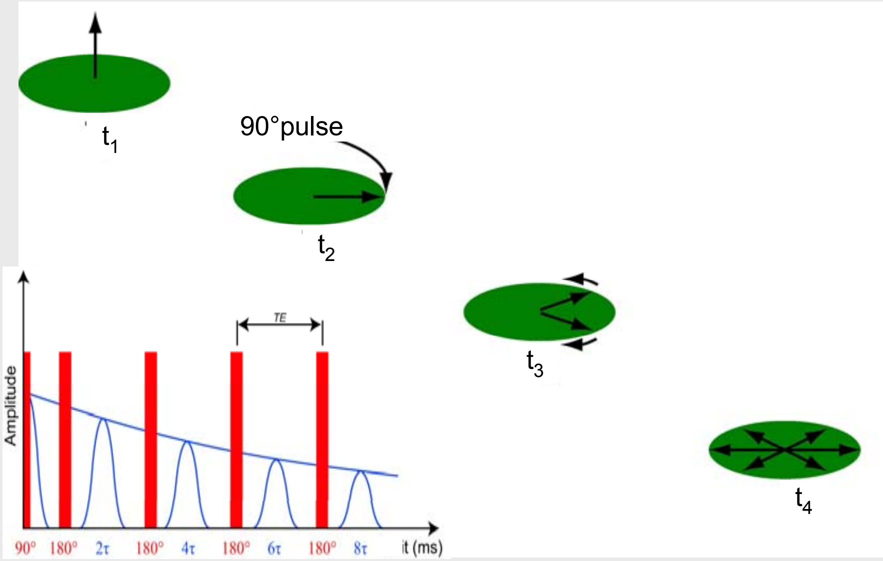


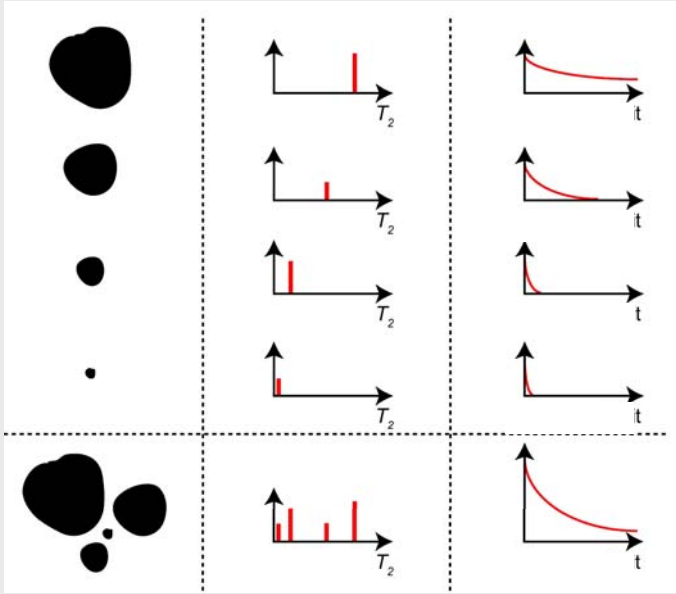


T_1 relaxation time: alignment of proton spins in external field → porosity

NMR Relaxation – T_2







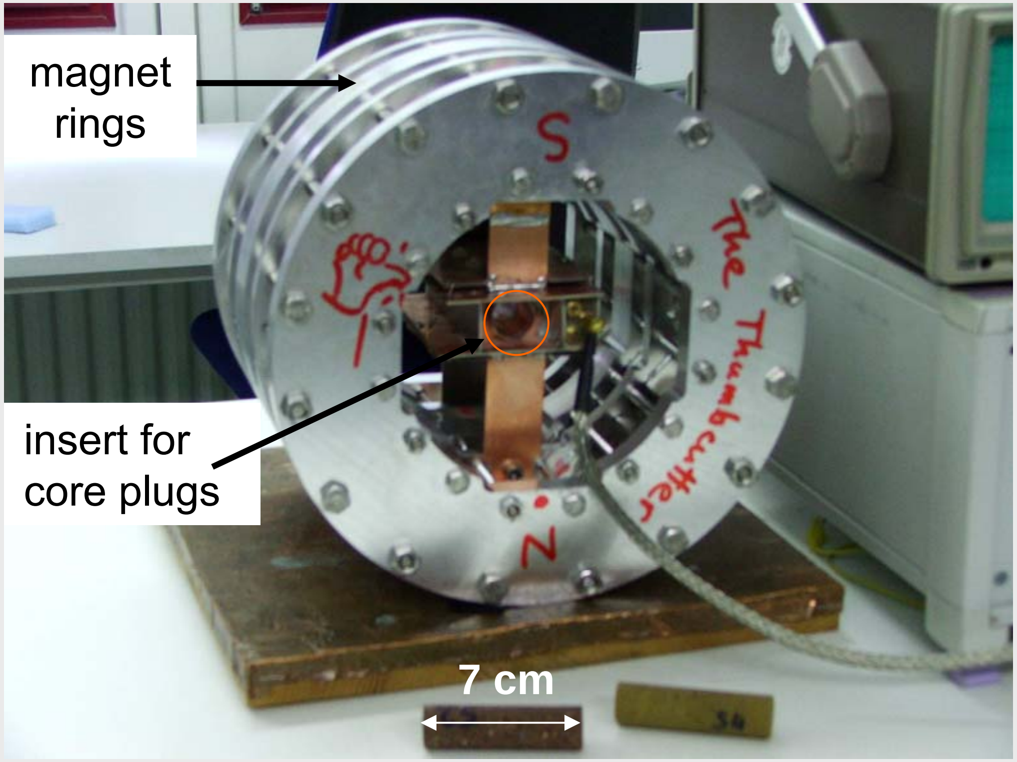
T_2 realxation time: repeated tipping of spins by external radio-frequency field B_1 followed by decay of transverse magnetization

→ T_2 decay curve;

→ pore size distribution;

→ permeability

Halbach core-scanner



- **Weight: 8 kg**
- **B_0: 0.3 T**
- **G: 0.3 T/m**
- **Frequency: 13 MHz**

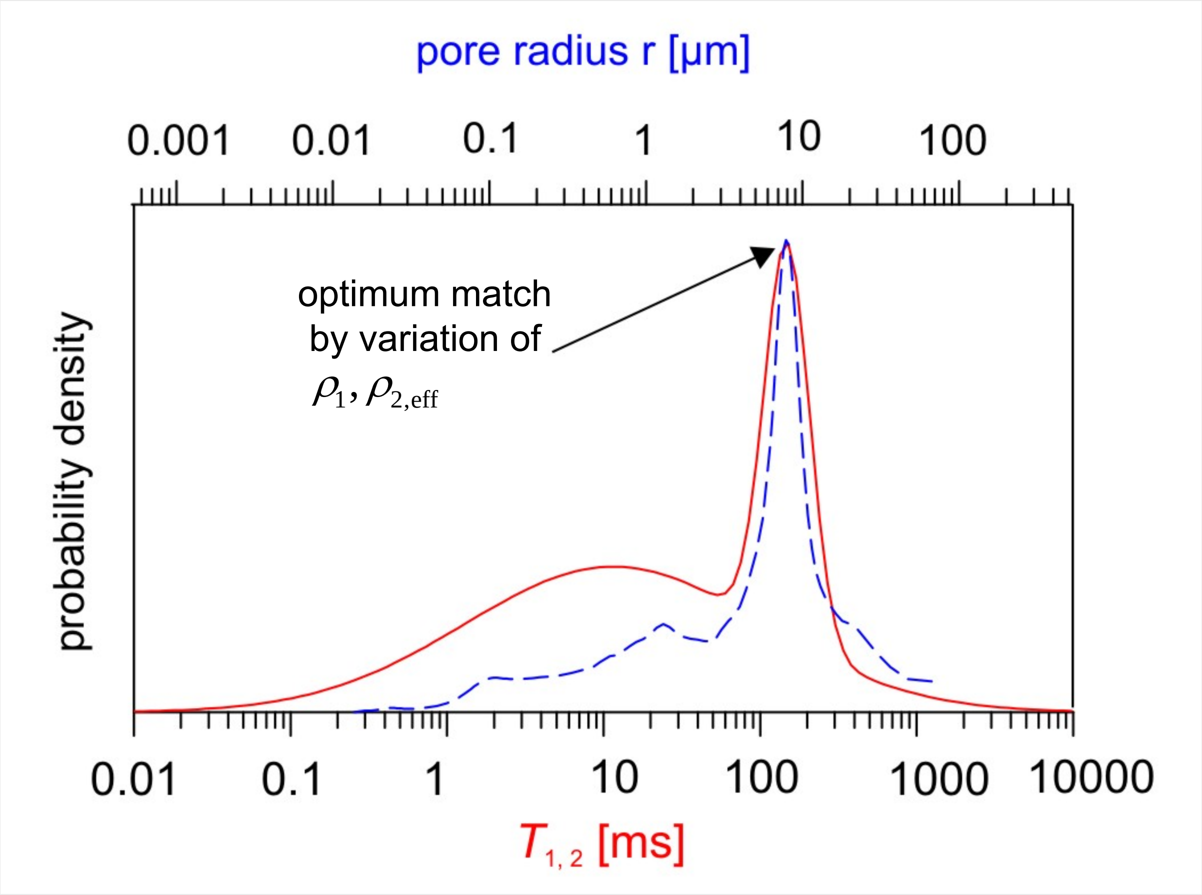
Anferova, S., Anferov, V., Arnold, J., Talnishnikh, E., Voda, M. A., Kupferschläger, K., Blümler, P., Clauser, C., Blümich, B., 2007. Improved Halbach Sensor for NMR Scanning of Drill Cores, *Magnetic Resonance Imaging, 25*, 474–480.

NMR Relaxation Rates

$$\frac{1}{T_{1\,\text{apparent}}} = \cancel{\frac{1}{T_{1\,\text{free fluid}}}} + \frac{1}{T_{1\,\text{surface}}}$$

$$\frac{1}{T_{2\,\text{apparent}}} = \cancel{\frac{1}{T_{2\,\text{free fluid}}}} + \frac{1}{T_{2\,\text{surface}}} + \frac{1}{T_{2\,\text{diffusion}}}$$

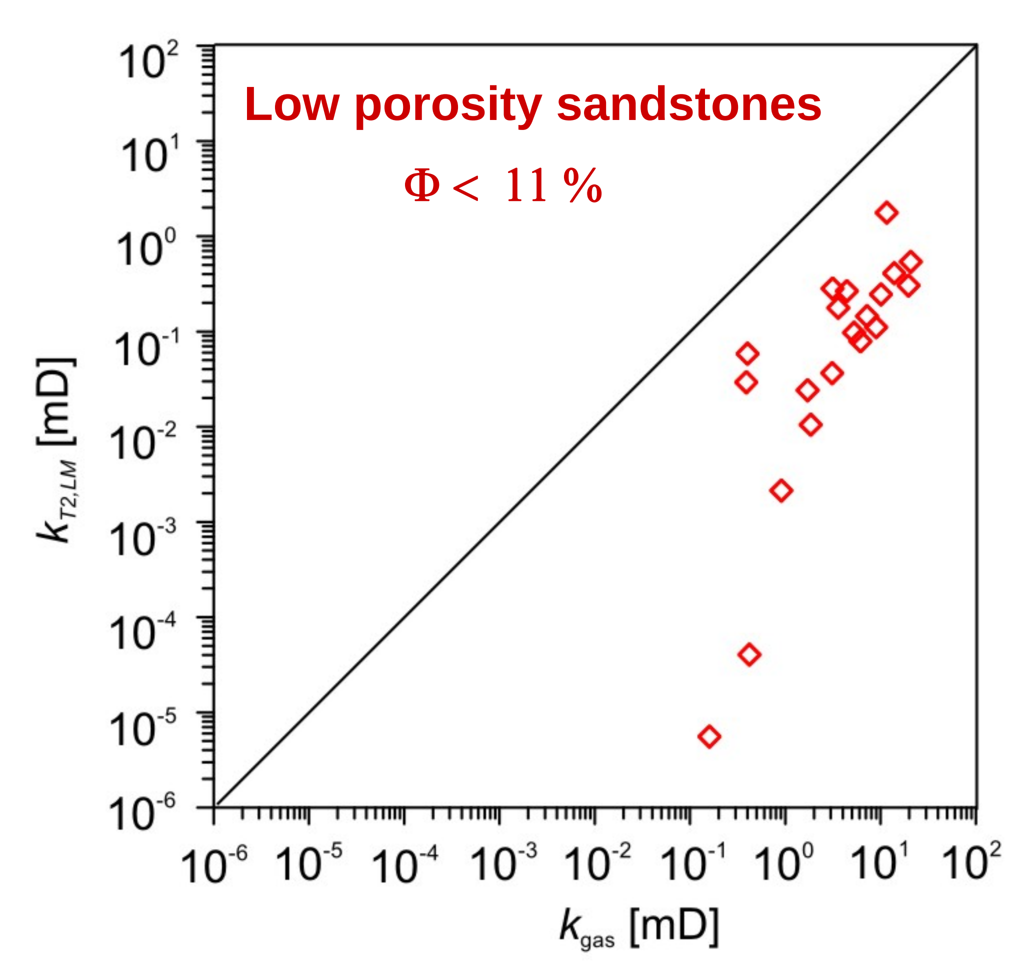
Surface Relaxivity



$$\frac{1}{T_{1,2}} = \frac{3\,\rho_{1,2\mathrm{eff}}}{r}$$

ρ : surface relaxivity [µm/s]

Standard equation for permeability



[2] Kenyon et al., 1988.

$$k_{T_{2,\mathrm{LM}}} = \mathrm{a}\ T^{2}_{2,\mathrm{LM}}\ \Phi^{4}$$

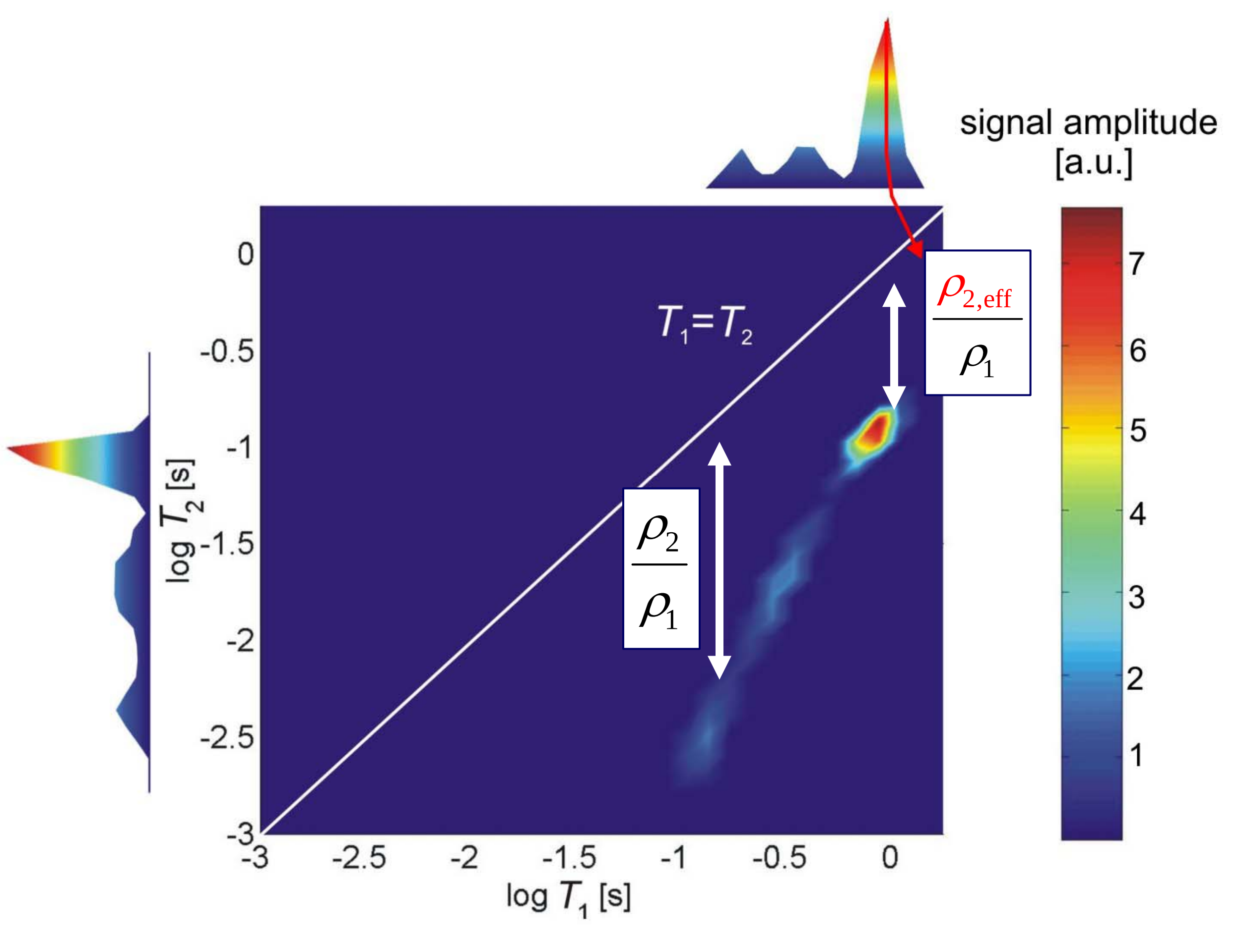
$\mathrm{a} = 4\ \mathrm{mD/ms^2}$

k : permeability [md]

$T_{2,\mathrm{Lm}}$: logarithmic mean of T_2 [ms]

Φ : porosity [-]

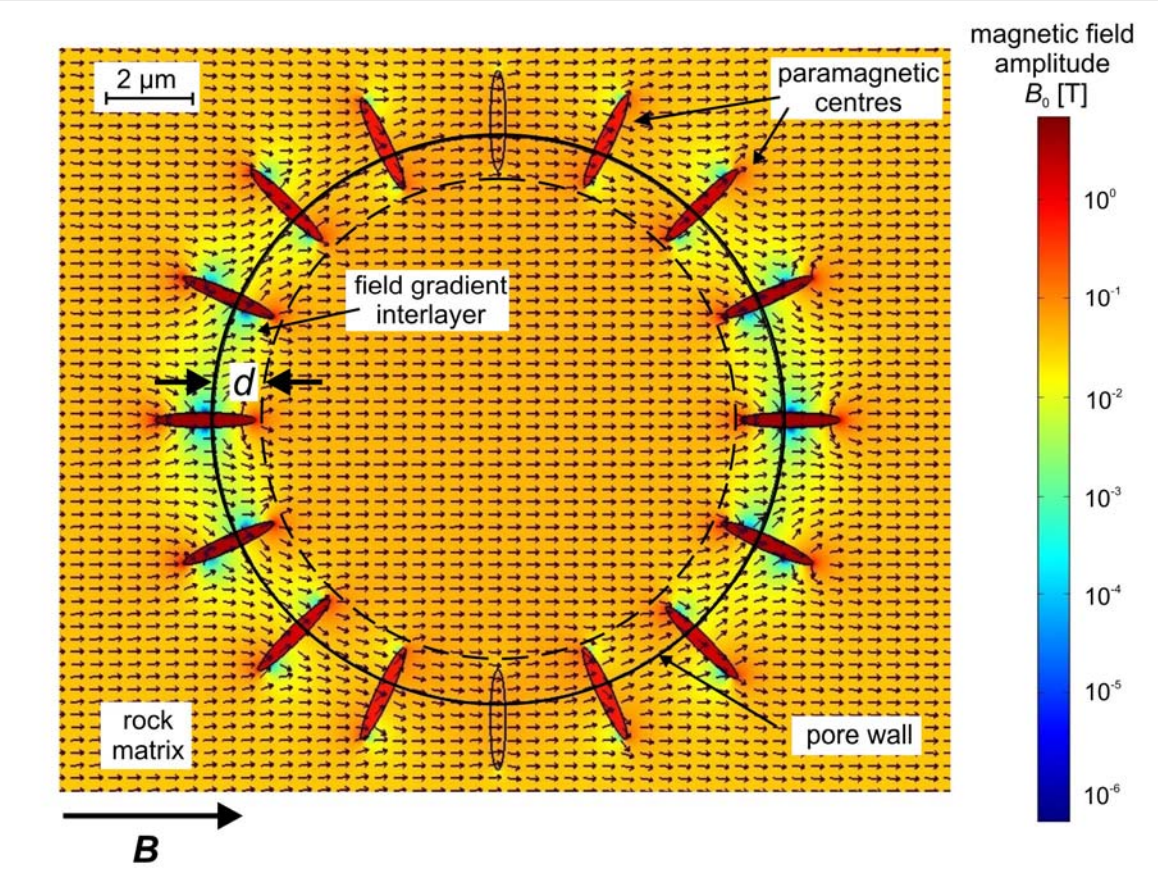
2D T1-T2 correlation map



Sandstone sample

AC15: Φ = 9 %

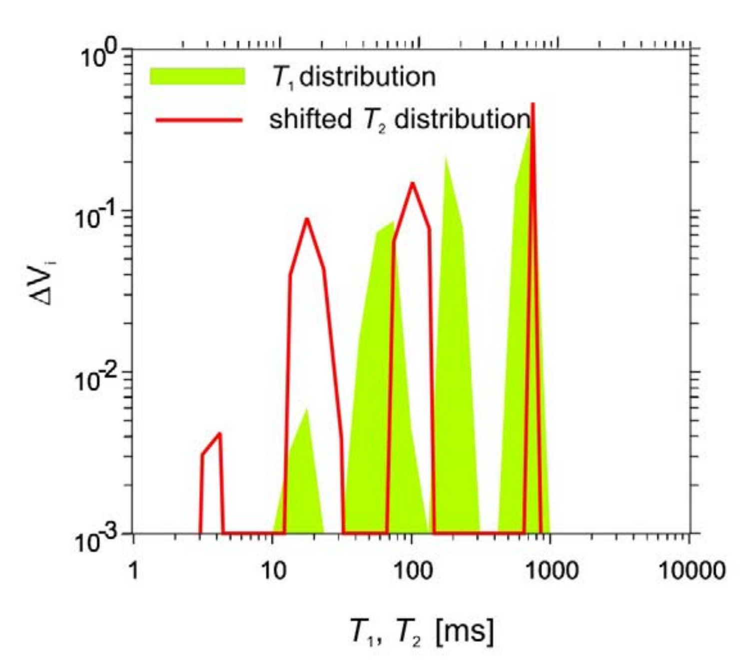
New Model Theory



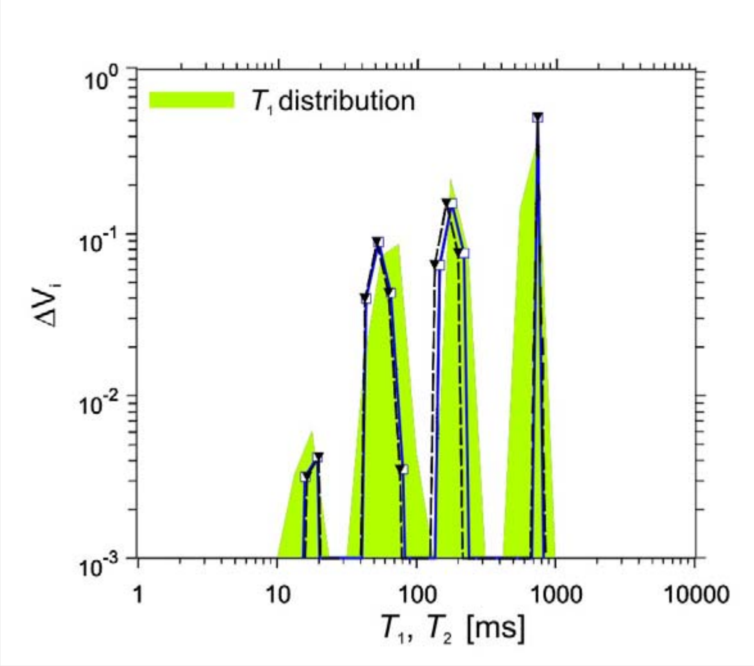
$$\boxed{\frac{1}{T_{2,\mathrm{ifg}}} = \frac{3\rho_{2,\mathrm{ifg}}}{r - d}}$$

$$\frac{1}{T_{2\ \mathrm{apparent}}} = \frac{1}{T_{2\ \mathrm{free\ fluid}}} + \frac{1}{T_{2\ \mathrm{surface}}} + \frac{1}{T_{2\ \mathrm{diffusion}}}$$

Correction of T2 distribution



Correction of T_2



based on:

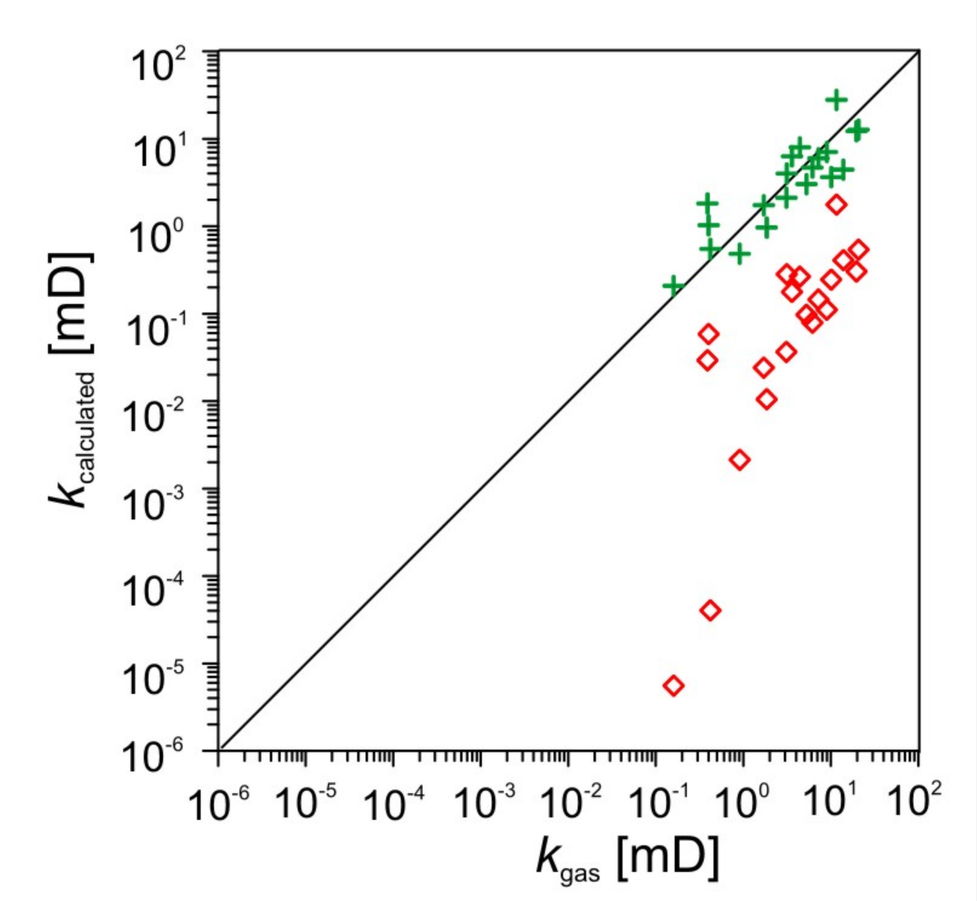
model theory:

$$\rho_2 = \rho_1 + \frac{\rho_{2,\mathrm{ifg}}}{\left(1 - \frac{d}{r}\right)}$$

empirical equation:

$$r_{\mathrm{corr}} = r_{\rho_{2,\mathrm{eff}}} \left(\frac{9.53}{r_{\rho_{2,\mathrm{eff}}}} \right)^{0.3}$$

Permeability results



Kozeny-Carman equation using r_{corr} ($T_{2,LM}$):

$$k = \left(\frac{1}{8}\right)\frac{\Phi}{T} r^2_{\mathrm{corr}}(T_{2,\mathrm{LM}})$$

T : tortuosity

Standard $T_{2,LM}$ equation:

$$k = \mathrm{a}\ T^2_{2,\mathrm{LM}}\ \Phi^4$$

Conclusions

✓ Mobile tool for use on drilling platforms

✓ Standard permeabilty calculation scheme for high porosity rocks

✓ Improved permeability prediction for low porosity rocks taking into account increasing diffusion effects

! Individual calibration required for each formation

Acknowledgments

to the German Science Foundation (DFG)

for operating grants

BL 231/26-1/2 to B. Blümich and

CL 121/16-1/2 to C. Clauser

within the DFG ODP/ICDP priority program.